AUSTRALIAN ATOMIC ENERGY COMMISSION

RADIOACTIVE WASTE MANAGEMENT

by

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ABSTRACT

Present and future methods of managing radioactive wastes in the nuclear industry are reviewed. In the stages from uranium mining to fuel fabrication, the main purpose of waste management is to limit and control dispersal into the environment of uranium and its decay products, particularly radium and radon. Nuclear reactors produce large amounts of radioactivity but release rates from commercial power reactors have been low and well within legal limits.

The principal waste from reprocessing is a high activity liquid containing essentially all the fission products along with the trans-uranium elements. Most high activity wastes are currently stored as liquids in tanks but there is agreement that future wastes must be converted into solids. Processes to solidify wastes have been demonstrated in pilot plant facilities in the United States and Europe. After solidification, wastes may be stored for some time in man-made structures at or near the Earth's surface. The best method for ultimate disposal appears to be placing solid wastes in a suitable geological formation on land.

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LIQUID WASTES; MILLING; MINING; NUCLEAR INDUSTRY; RADIOACTIVE WASTE DISPOSAL; RADIOACTIVE WASTE STORAGE; REPROCESSING; SOLID WASTES; SOLIDIFICATION; TRANSPORT; URANIUM ORES.

CONTENTS

RADIOACTIVE WASTE MANAGEMENT

SUMMARY

The nuclear industry embraces all activities connected with the production of electricity from fissionable materials. Radioactive waste management aims to ensure that radiation exposure to the public from these activities is kept well within any legislated requirements and small compared to that received from the natural environment.

Uranium has a long half-life (4.51 billion years for uranium-238) and decays through a chain of radioactive daughter products of which radium-226, radon gas and its decay products are the most hazardous. In the stages from uranium mining to fuel fabrication, the main purpose of waste management is to limit and control dispersal of uranium and its daughter products into the environment. The effluents are essentially chemical in nature, contaminated with some naturally occurring radioactivity from uranium and its decay products.

Nuclear reactors produce large amounts of radioactivity, principally by nuclear fission. Absorption of neutrons in the fuel results in the formation of the transuranium elements, neptunium, plutonium, americium and curium. In addition, some radioactivity is induced in the structural materials of the reactor core and in the coolant. Isotopes of most importance are fission products and transuranium elements with long decay half-lives and high radiotoxicity in the body. Almost all the radioactivity generated is retained within the fuel elements during reactor operation. Small amounts of volatile fission products escape from the fuel and are discharged to the atmosphere after treatment to retain radioactive iodine and filtration to remove particulates. Ion exchange resins are used to remove radioactivity in the recirculating coolant. Solid wastes include contaminated equipment and waste resins and these are generally packaged before disposal by burial.

Discharged fuel is stored under water, to allow substantial decay of the isotopes with short half-lives, then transported to a reprocessing plant where the valuable uranium and plutonium are recovered. Spent fuel has been transported for many years without injury to the public.

The principal waste from reprocessing is a high activity liquid containing essentially all the fission products and the remaining transuranium elements. This is the most radioactive waste in the entire nuclear fuel cycle and of major importance in waste management. Most high activity wastes are stored as liquids in tanks which vary in size from 50 to

5000 cubic metres. Some tanks in the United States, built to hold liquid wastes generated by the weapons program and other government operations, have leaked but radioactivity has not migrated beyond the immediate vicinity of the tanks. These tanks were not designed or constructed to sufficiently high standards and surveillance has not always been adequate. Modern tanks have double containment, with monitoring equipment to detect leaks. There is now agreement in countries with nuclear power programs that wastes must be converted into solids which will be safer for long-term storage, minimise waste volume, and decrease or eliminate the need for surveillance. Processes to solidify wastes, including conversion to glassy solids of low solubility in water, have been demonstrated in pilot plant facilities in the United States and Europe.

After solidification, wastes may be stored for some time in man-made structures at or near the Earth's surface. Methods for final disposal of the wastes are being studied, including storage in geological formations on land (such as salt deposits or hard rock), in ice-sheets or in the sea bed. Complete elimination of the transuranium elements, some of which remain a hazard for up to one million years, may be feasible either by transportation to outer space or by transmutation in a reactor into fission products which decay to inactive elements within a thousand years.

The best method for ultimate disposal appears to be to place solid wastes in a suitable geological formation on land. Disposal in salt or hard rock does not require a new technology but it does require confirmation that wastes will remain permanently out of man's environment. Until a satisfactory ultimate disposal method is fully proven, the nuclear industry has a responsibility to maintain strict surveillance of high activity wastes.

1. INTRODUCTION

Waste is an inevitable by-product of all industries. In many respects, the wastes from the nuclear industry are similar to those encountered whenever chemicals are manufactured and processed. However, wastes from the nuclear industry generally contain radioactivity, undetectable by the senses, but potentially hazardous to man. The methods used in managing radioactive wastes are designed to minimise their impact on the environment and to ensure that the radiation exposure to the public is kept well within any legislated requirements and small compared to that received from the natural environment.

This paper outlines the general principles of radioactive waste management and describes the types of wastes arising in the nuclear industry, especially from mining and milling of uranium ores, operation of nuclear power reactors and reprocessing of irradiated fuel. Methods of treating these wastes are summarised. Present practice and future plans for storage, solidification, transport and ultimate disposal of high activity wastes from fuel reprocessing are described.

2. PRINCIPLES OF RADIOACTIVE WASTE MANAGEMENT

There are three basic principles of radioactive waste management which may be expressed simply as:

- Delay and decay
- Concentrate and confine
- Dilute and disperse

'Delay and decay' applies particularly to radioisotopes of short half-life which decay to stable elements if stored for a sufficient time.

'Concentrate and confine' implies that the volume of the radioactive waste is reduced, but the waste retains its identity and is confined in a controlled location from which it can be retrieved.

'Dilute and disperse' applies where the radioactivity can be reduced to acceptable concentrations by dilution in the environment. Before radioactivity is released to the environment, it is necessary to evaluate quantitatively the physical, chemical and biological routes by which it could reconcentrate and return to man.

3. THE NUCLEAR INDUSTRY

The nuclear industry comprises all the activities connected with the use of reactors to produce electricity from fissionable materials as well as the utilisation of radioisotopes and radiation in medicine, industry and research.

It therefore includes:

- exploration for uranium,
- mining and milling of uranium ore to produce a uranium concentrate known as yellowcake,
- conversion of yellowcake to uranium hexafluoride,
- enrichment of uranium to increase the content of the isotope uranium-235,
- fabrication of fuel elements,
- operation of nuclear power reactors,
- reprocessing of irradiated fuel to recover residual uranium and plutonium, and
- treatment, storage and/or disposal of radioactive wastes.

Not all reactors require all of these steps. Although there may be differences which affect particular treatment procedures, the waste management principles used throughout the industry are the same.

Table 1 summarises the radioactive wastes in the above steps in the nuclear industry and typical practices for their management. The stages requiring most attention are uranium mining and milling, reactor operation and, particularly, reprocessing of irradiated fuels and the ultimate disposal of fission products and transuranium wastes.

4. URANIUM MINING AND MILLING

Uranium ores typically contain only a few tenths of one per cent of uranium (a few kilograms per tonne of ore) and are treated in a mill located close to the mine to produce yellowcake, a concentrate of uranium oxides, for shipment.

Natural uranium is a radioactive material with a long half-life (4.51 billion years for uranium-238) and decays through a chain of radioactive daughter products. The most hazardous of these daughter products are radium-226 and radon-222 gas and its daughter products. In mining, the frequency of lung cancer is increased by exposure to radon daughter products and chemically active dusts in the air, and limits to exposure are provided in the new Australian Code on Radiation Protection in the Mining and Milling of Radioactive Ores at present in draft form. Radon concentrations encountered in opencut mining are generally low, but in some cases, a supply of clean air may be necessary for operators of the mining equipment as provided for in the Australian Code. In underground mining, forced ventilation is essential. In both cases, strict monitoring is required.

In the uranium mill, the ore is crushed and ground, then leached with acid or alkaline solutions (depending on the nature of the ore) to extract the uranium which is then recovered by solvent extraction or ion exchange and converted to yellowcake by precipitation and heating (calcination). Part of the solution which remains after the uranium is recovered is recycled in the plant and, if acid leaching is used, the remainder is usually made alkaline before storage with the solid waste.

The majority of the ore is not dissolved in the leaching stage and is a waste product called tailings which still contain most of the natural radioactive daughter products originally in the ore. The tailings are usually pumped as a slurry into a specially constructed retention system where they are confined. Control of tailings is necessary to minimise the dust nuisance, limit natural leaching and seepage from the retention system which could lead to ground-water pollution, and prevent access to the tailings by the public. In the past, adequate care has not always been taken to prevent dispersal of tailings in the environment. Possible future approaches include returning the tailings to fill worked-out mines or covering the tailings with soil and revegetating the whole area to stabilise it.

The liquid effluents which arise from uranium mining and milling (and also in the subsequent steps of conversion of concentrates to uranium hexafluoride, enrichment and fuel fabrication) are essentially chemical waste streams containing nitrate, sulphate, ammonia, fluoride etc., and traces of uranium and its daughter products. They are treated by conventional methods such as neutralisation with lime to concentrate the wastes for disposal, generally by burial, as shown in Table 1.

5. REACTOR OPERATION

During reactor operation, large amounts of radioactivity are produced by three processes: fission in the fuel (the major source), absorption of neutrons in the fuel to form the transuranium elements (neptunium, plutonium, americium, curium), and neutron activation of the coolant and structural components of the reactor. The fission products and transuranium elements are retained within the fuel elements by the fuel cladding. Some fission products may be released into the coolant if the fuel cladding is perforated but, even in these circumstances, the majority of the fission products are retained in the ceramic fuel pellets.

Small quantities of gaseous, liquid and solid wastes are produced (see Table 1). Gaseous activation products and small amounts of volatile

fission products which may leak from the fuel, for example iodine, krypton and the xenon isotopes, are passed through charcoal adsorbers which remove iodine, then filtered and discharged to the atmosphere. Activation products and fission products from uranium contamination on the surface of the cladding or leaks from the fuel are recovered from the recirculating reactor coolant by filtration and ion exchange equipment. Liquid wastes are treated by evaporation, ion exchange or chemical methods to produce purified water for recycle or discharge to the environment while the bulk of the radioactivity is confined in a sludge or concentrated solution.

A variety of low and medium activity solid wastes, including ion exchange resins, sludges from treatment of waste solutions, and general waste materials, such as contaminated equipment and clothing, also have to be treated before storage or disposal. The method of disposing of solid wastes depends on the nature and level of activity in the wastes. Low activity wastes are usually buried in relatively shallow trenches at selected sites at or near nuclear facilities after evaluation of the local geology and hydrology has indicated low rates of migration of radioactivity. The original predictions are checked by environmental monitoring programs. Depending on the activity level or the desire to minimise the extent of surveillance required, releases of radionuclides to the environment may be further reduced by incorporating low and medium activity wastes in concrete or bitumen before burial. In some countries, medium activity wastes are stored in concrete silos for retrieval if necessary.

In practice, releases of radioactivity from commercial power reactors have been low and well within legal limits.

6. REPROCESSING OF IRRADIATED FUEL

After the irradiated fuel is discharged from the reactor, it is stored in water-filled ponds which cool the fuel, provide shielding from radiation, and allow the radioisotopes with relatively short half-lives to decay substantially. The fuel is then transported to a reprocessing plant where the residual uranium and plutonium are recovered for re-use. At present, there is insufficient capacity to reprocess irradiated fuel, particularly in the United States, and storage in ponds may be necessary for several years before new and expanded plants are operational.

In reprocessing, the fuel element is cut into small pieces to expose the fuel which is dissolved in nitric acid. An organic solvent, commonly tributyl phosphate, is used to extract typically 99.5 per cent of the uranium and plutonium from the acidic solution and less than 0.1 per cent

of the fission products. The solution containing the remaining uranium, plutonium, fission products, and all the other transuranium elements is concentrated by evaporation to reduce its volume for storage. It is this high activity liquid waste which is of major importance in radioactive waste management (see Section 7).

The extracted uranium and plutonium are put through additional solvent extraction or ion exchange steps to separate and purify the elements and these processes result in medium and low activity radioactive waste solutions. The medium activity liquid wastes are concentrated by evaporation, the concentrate being combined with high activity wastes and the remainder combined with low activity liquid waste. The low activity liquid wastes are also treated, usually by ion exchange, to concentrate the radioactivity for storage and enable the bulk of the water to be recycled in the plant or discharged and diluted in the environment.

During cutting and leaching of the fuel, tritium and gaseous fission products, including iodine, krypton and xenon isotopes, are released from the fuel. Of these, radioactive iodine is the most significant biological hazard. Fortunately, the iodine isotope produced in the largest quantity, iodine-131, has a half-life of only eight days and decays to a low activity during fuel element cooling before reprocessing. The remaining iodine-131, along with another isotope, iodine-129, which has a half-life of 16 million years, is absorbed in nitric acid and caustic solutions, sometimes followed by adsorption on beds of silver zeolite. The waste solutions resulting from treatment of gas streams containing iodine are treated as high activity waste.

The radioactive noble gases, krypton and xenon, which are not biologically active and tritium,are usually discharged through tall stacks to obtain sufficient dilution in the atmosphere. Radiation doses to the population from these emissions are currently well within the recommendations of the International Commission on Radiological Protection. In the future, emissions from large reprocessing plants will lead to a global buildup of krypton-85 (half-life 10.7 years) and tritium (half life 12.3 years) resulting in radiation doses which will be a fraction of one per cent of the natural radiation background. Processes for the removal of krypton from off-gases are under development using techniques such as absorption in Freon, adsorption on charcoal, and distillation at liquid nitrogen temperatures. Methods of separating tritium by heating the fuel before it is dissolved, or by using processes which rely on differences in the

chemical properties of hydrogen and tritium compounds, are also being investigated.

A variety of solid wastes are generated during reprocessing. Low and medium activity solid wastes are treated in a similar manner to those arising from reactor operation (Section 5). The chopped cladding that remains after the fuel has been dissolved is highly radioactive as a result of neutron activation in the reactor and because it also retains up to 0.1 per cent of the fuel which is difficult to remove completely. Usually, this cladding is stored in concrete-lined silos as an interim measure and may be retrieved from the silos for final disposal.

In the early years of the nuclear weapons program in the United States, wastes contaminated with transuranium elements, mainly plutonium, were frequently buried under the same conditions as for other radioactive wastes. However, because of the very long half-life of plutonium and its high radiotoxicity, this practice was stopped in 1970. These wastes are currently stored in various ways which will enable them to be retrieved. Emphasis is now being placed on schemes to limit the volume of waste initially produced and then to treat it to further reduce its volume. Techniques such as combustion, and digestion in acid, are under investigation. Storage of the concentrated wastes from these processes would then receive the same consideration as storage of high activity solid wastes.

7. HIGH ACTIVIVITY WASTES

7.1 Nature of High Activity Liquid Wastes

More than 99 per cent of the activity in the irradiated fuel enters the high activity liquid waste during reprocessing. Tables 2 and 3 list the radioactivity of the more important fission products and transuranium elements in high activity liquid wastes at various times after discharge of the fuel from a reactor. There are over 200 different species of fission products but the ones that have most importance in waste management are those produced in large quantities in the reactor, have long decay half-lives and significant radiotoxicity in the body, particularly caesium-137 and strontium-90.

Although the fission products pose the greatest radiation hazard for several centuries, they do not constitute a significant environmental problem beyond a thousand years. The total radioactivity of the fission products after a thousand years is less than the radioactivity in the ore from which they were derived. The transuranium elements are the major concern after about eight hundred years because of their long half-lives

and greater radiotoxicity. After one thousand years, their activity is still about three times that of the ore from which they were derived.

7.2 Storage of Liquid Wastes

Most of the high activity wastes that have been produced from reprocessing of nuclear fuels in various countries are now stored as liquids in underground tanks. The size of these tanks varies from about 50 cubic metres to about 5000 cubic metres. Stainless steel tanks are used for acid wastes. Mild steel tanks are commonly used to store wastes that have been made alkaline. Unless the tanks are cooled, liquid wastes when first produced will boil from the heat generated by radioactive decay of the fission products. One year after discharge from a modern light water reactor, the heat generation rate is about 8 kilowatts per cubic metre. Heat is removed from the high activity storage tanks either by installing internal cooling coils to keep temperatures below 65°C or by allowing the liquid to boil and condensing the steam produced.

The first high activity wastes were produced in the USA during the Second World War as part of the nuclear weapons program and stored in steel-lined concrete tanks. Originally, the recovery processes were very inefficient and large volumes of wastes were produced. The USA has built about 200 tanks to hold the high activity liquid wastes generated by the weapons program and other government operations. The older tanks were not designed or constructed to sufficiently high standards and surveillance has not always been adequate. Ten per cent of these tanks have leaked but radioactivity has not migrated beyond the immediate vicinity of the tanks and no contamination of ground-water has been detected.

The design of a modern storage tank for alkaline waste is illustrated in Figure 1 and reflects improved design over the past two decades. In this design, a stress-relieved, free-standing, carbon-steel tank is completely enclosed in a fully steel-lined concrete vault. The storage system is designed to withstand natural forces such as a severe earthquake without leakage. To escape to the environment, waste would have to penetrate three layers of containment, two of steel and one of concrete. Monitoring equipment is located between the two tanks to detect any leak from the primary containment. Should this occur, waste can be transferred to spare tankage which is always kept available.

Stainless steel tanks with double containment and internal cooling coils have proved to be most reliable for storage of high activity acidic wastes in the United Kingdom, France and the USA and are becoming

increasingly common throughout the world. For example, at Windscale, the site of the major reprocessing facilities in the United Kingdom, eight tanks each with a capacity of 70 cubic metres, and three with a capacity of 150 cubic metres, are available to store high activity liquid waste. Two large tanks are under construction. This system of storing wastes as acidic solutions has been in use for about 20 years and no leaks have occurred. It has the added advantage of minimising waste volume and preserving maximum flexibility for subsequent processing.

A 1000 megawatt reactor, capable of supplying the electric power requirements of a city of one million people, gives rise to about 34 cubic metres of high activity liquid waste per year. Taking into account the future growth of the nuclear industry, the total world production rate of high activity liquid wastes is likely to be about 6000 cubic metres in 1980, 33 000 cubic metres in 1990 and 95 000 cubic metres in the year 2000. This is to be compared with the 320 000 cubic metres now stored in the United States, mainly produced in the weapons program and other government operations. Because of improvements in the technology of waste processing, the civilian nuclear power program in the United States up to the year 2000 will generate a smaller volume of high activity wastes than that now held at government plants at Hanford, Savannah River and Idaho Falls.

The experience in storage of large quantities of wastes as liquids over the past twenty years has demonstrated that the above method is a satisfactory approach provided surveillance is maintained, spare tanks are available in case of unexpected failures and a policy of adequate tank replacement is instituted. But there is now agreement throughout the world that prolonged liquid storage must soon give way to a solidification program that will increase the integrity of waste confinement, make surveillance less vital and reduce the requirement for tank replacement.

7.3 Waste Solidification

Conversion of high activity liquid wastes into solids has a number of advantages over liquid storage for an indefinite period:

- Solids are less mobile than liquids. Obviously, they cannot leak as liquids do and they are also more difficult to disperse by any means. Therefore the need for surveillance is reduced.
- Waste volume is minimised. Solidification reduces volume by a factor of ten or more.

- The most desirable solid forms are not easily dissolved by water.
- Solids are more rugged and can be transported.

Work on the solidification of wastes began over twenty years ago and in the United States, United Kingdom, France and Germany, particular processes have been tested in pilot plant facilities. Though there are many minor variations, mostly of an engineering nature, two approaches have received most attention. The first is to dehydrate and decompose liquid wastes by heating (calcination) to form a solid. In the second, glass or ceramic forming mixtures are added to the wastes and the mixture is heated to form a melt that cools to a solid cylindrical block. Borosilicate glass (Pyrex) and phosphate glasses as well as ceramics have been formed by this technique. These two general methods of solidification are not mutually exclusive. For example, a calcined product may prove to be a more suitable form for interim storage, but for final storage, a less leachable form such as borosilicate glass appears more desirable.

In the United States, France and Germany, a decision has already been taken that highly radioactive wastes will be stored as solids (see Appendix). Future commercial wastes produced in the United States must be converted to an approved solid form within five years of reprocessing. All the United States government plants have continuing programs to solidify their wastes. At the National Reactor Testing Station near Idaho Falls, more than 9000 cubic metres of liquid wastes has been solidified since 1963 using a calcination process in a fluidised bed and this method has been proposed for commercial high activity wastes. Several other processes for waste solidification have been demonstrated at Hanford on a scale equivalent to the production of waste from the fuel from ten 1000 megawatt light water reactors. The next step would appear to be commercial application. This will occur by the early 1980s when sufficient commercial wastes have been accumulated to justify processing.

7.4 Interim Storage of High Activity Solid Wastes

Although a stable solid is the most desirable form for storage of high activity wastes, it is still necessary to ensure that wastes remain separated from the biological environment until they decay to innocuous levels. For fission products, this period is five hundred to one thousand years; for transuranium elements, it is perhaps up to one million years.

Many methods for ultimate disposal have been proposed, but many nations consider that the best policy for the near term is interim storage

in man-made structures at or near the surface of the Earth. 'Engineered storage', as this approach is called, has the advantage that continuous surveillance can be maintained and solid wastes can be more easily cooled at a time when their heat generation rate is greatest. It also has the advantage of providing more time for detailed evaluation of the many options available for elimination or ultimate disposal of wastes.

A number of different designs for a retrievable surface storage facility have been examined in the United States and France. All proposals for engineered storage involve first loading the waste into stainless steel canisters. Ten canisters, each of 0.3 metre diameter and 3 metres long, would be required each year for the waste from a 1000 megawatt (electrical) reactor. These canisters would then be stored either individually in the open in shielded casks, in air-cooled vaults, or in water-cooled ponds. The last approach is similar to that currently used to store irradiated fuel assemblies discharged from a reactor. All the necessary technology is available for constructing and operating a retrievable storage facility for periods of up to 100 years.

In the United States, assuming storage in water-cooled ponds or air-cooled vaults, the land requirement for a retrievable surface storage facility is estimated to be ~~25~~ 40 hectares (100 acres) up to the year 2010. Similarly in the United Kingdom it has been estimated that, in the year 2000 when three-quarters of their electricity will be generated by nuclear power, the total land area occupied by interim liquid storage tanks and ponds containing waste canisters will be only 0,7 hectares (~~30~~ 2 acres), about the area of two football grounds.

8. ULTIMATE DISPOSAL OF HIGH ACTIVITY WASTES

Engineered storage can only be considered an interim solution because no man-made structure can be expected to withstand the natural environment for an indefinite time. Concepts for ultimate disposal on Earth involve storage in geological formations on land, in ice sheets or in the seabed.

8.1 Geological Formations on Land

This has particular appeal because many geological formations have been physically and chemically stable for many millions of years. Of all ultimate storage concepts, disposal in salt mines has been most extensively researched. Salt deposits were formed many millions of years ago and, since salt is soluble in water, their very existence is proof that they have never been subjected to major water erosion. Decay heat from the waste

would be dissipated easily because salt is a good conductor of heat. In the salt disposal concept, encapsulated solids are placed in vertical holes in the floor of an excavated cavern deep underground. The holes are backfilled with two to three metres of crushed salt. After a few decades, the salt will flow plastically, owing to the pressure of the overburden, and permanently seal the waste in salt.

About twenty years ago, the United States Atomic Energy Commission began studying the feasibility of storing solid wastes in salt and extensive tests were carried out in a bedded salt deposit at Lyons, Kansas. The technical results were generally encouraging but the site was abandoned a few years ago when it was discovered that a number of man-made wells had been drilled in the deposit. In addition, commercial recovery of salt by solution mining was being expanded near the test site. Surveys have since been undertaken to find a more suitable site and a number of locations in New Mexico appear to be promising. In West Germany, an abandoned salt mine at Asse is already being used for disposal of low and intermediate activity solid wastes. Experimental studies using high activity glassified wastes are scheduled to begin in a few years.

A number of other geological formations including shales and granites are being studied for suitability as waste repositories. Some concepts, involving storage in mined cavities in these rocks, could have the added attraction of retrievability should the need arise. Solid emplacement in holes as deep as 16 km has been suggested as a method of ensuring prolonged removal from man's environment. This plan is not technically feasible at present and could be expensive.

Other concepts include injection of high activity liquid wastes into deep wells or underground cavities produced by nuclear blasts. The initial heat generated by the wastes is sufficient to melt the surrounding rock but eventually the waste cools and is incorporated in a solid rock-waste matrix. In general, concepts for disposal of wastes as liquids appear to offer less guarantee of permanent removal from the biosphere.

Many factors must be considered in the selection of a geological site for ultimate disposal. The site must be located in a region with a very low frequency of earthquake and volcanic activity. Hydrological conditions such as rock permeability and the existence of ground-water in the region are important. The area should also have poor potential for future oil, natural gas or mineral exploitation. Despite these and other restrictions, there should be no particular difficulty in finding suitable

sites for ultimate disposal because the land requirement is not large. For example, it has been estimated that less than 800 hectares (about three square miles) of salt would be required to store all high activity wastes generated by the nuclear industry in the United States until the end of this century.

8.2 Ice Sheets

Like salt, ice sheets flow plastically and are self-sealing. Their other advantages include remoteness from large populations and good heat transfer. One concept for disposal in ice involves placing each waste canister in a drilled hole and allowing it to melt its way through the ice sheet to bedrock. Another approach is to use anchors to hold each canister at a predetermined depth of about 100 metres. The feasibility of these concepts depends on the rate of lateral movement of ice in the region near the disposal site and the nature of the interface between ice and bedrock. In some ice sheet areas, this has been estimated to be so slow that the waste would be retained under the ice for over 100 000 years. Ice surges are known to occur and fundamental information on ice flow must be gathered before the merits of this approach can be fully assessed. Even if shown to be technically feasible, any proposal of this type for Antarctica would require amendment of the Antarctic Treaty of 1959 which prohibits the disposal there of any radioactive wastes.

8.3 Seabed

Several options for seabed disposal have been proposed. For example, one involves placing wastes in drilled holes in a deep ocean trench in a region where the seabed is moving under a continental plate (a large mass of the Earth's crust) at a slow rate and will eventually be incorporated into the mantle of the Earth. The appeal of this method is the possibility it offers of permanent isolation of the wastes. However, relatively little is known about the ocean floor and extensive research is required to assess the feasibility of this approach. All seabed disposal concepts have the disadvantage that sea water is corrosive and provides a ready means for dispersing any radioactivity that might be accidentally released.

8.4 Separation and Elimination of Transuranium Elements

Complete elimination of high activity wastes is the most appealing approach for ultimate disposal. This could conceivably be accomplished by either extraterrestrial disposal or transmutation of elements. It does not appear technically or economically feasible to eliminate all wastes but it may be possible to dispose of the long-lived transuranium elements

in this manner.

Before the transuranium elements can be eliminated, they must be very efficiently removed from the fission products; typically, recoveries must be 99.9 per cent for uranium, 95 per cent for neptunium, 99.95 per cent for plutonium and 99.9 per cent for americium and curium. Transuranium elements are already routinely recovered from fission products on a small scale by solvent extraction and ion exchange, but considerable development would be required to achieve these recoveries at large throughputs.

Extraterrestrial disposal involves transporting sealed capsules containing transuranium elements in space vehicles from the Earth. According to NASA experts, this could be achieved with current technology using a shuttle to transport the wastes into a circular Earth orbit. From this orbit, tugs containing the wastes could be launched into outer space. Many trajectories in space are possible including solar orbits and escape from the solar system either directly or via the planet Jupiter. Of course, any such concept would have to guarantee the integrity of the waste capsules if the launching failed. External radiation from a capsule would not be a significant problem because transuranium elements emit mainly short-range alpha particles. Extraterrestrial disposal appears to be the most expensive method of dealing with high activity waste but the cost would not be prohibitive; other methods discussed earlier would not significantly increase the cost of nuclear power.

The most promising means of transmutation is to recycle transuranium elements to a nuclear reactor where, by process of neutron absorption and fission, they will be converted ultimately to fission products of shorter half-life. Although present light water reactors can be used to transmute elements, a better approach would be to 'burn' the transuranium elements in fast breeder reactors where the neutron spectrum is more efficient for this purpose.

9. TRANSPORT OF IRRADIATED FUEL AND HIGH ACTIVITY SOLID WASTES

The most important shipments in the nuclear industry involving wastes are those of irradiated fuel from a reactor to a reprocessing plant and of solid high activity wastes to an engineered storage facility or final repository. It is not planned to transport high activity liquid wastes. In 1959, the development of regulatory standards for safe transport of radioactive materials was entrusted by the United Nations to the International Atomic Energy Agency (IAEA) and its recommendations have been widely

implemented for the various modes of transport by rail, road, sea or air.

Shipping containers for irradiated nuclear fuel are massive vessels weighing 30 tonnes or more and designed to dissipate heat from radioactive decay, to shield people from radiation, and to prevent release of any radioactivity under normal or accident conditions. Under IAEA regulations, they must be capable of withstanding the following simulated accident conditions in sequence without loss of containment:

1. A free fall of about 9 metres onto an unyielding surface.
2. A drop of one metre onto a 150 millimetre diameter steel bar, 200 millimetres long, with the container in the orientation to do maximum damage.
3. A 30 minute exposure to an 800°C fire.
4. Total immersion in water at a pressure equivalent to a head of 15 metres for eight hours.

Spent fuel has been transported for many years without overexposure or injury to the public. The number of shipments will increase as the nuclear industry grows. For example, it has been estimated that in the United States in the year 2000 there will be a total of 16 000 shipments of irradiated fuel and 250 shipments of high activity solidified waste. There have been no significant shipments of solidified high activity waste but it is generally acknowledged that these will pose less potential hazards than transportation of irradiated fuel since the volume, activity and heat generation rate of solid wastes will be lower.

Of course, shipment of any hazardous material involves some risk. This could be reduced if nuclear reactors, reprocessing plants, waste storage facilities and perhaps even final repositories were located at the one site. This concept of 'nuclear power parks' which is now being examined overseas has a number of economic advantages and would mean that many of the activities in the nuclear fuel cycle could be concentrated within the one security fence.

10. CONCLUSION

Modern practices of radioactive waste management in the nuclear industry are designed to ensure that exposure is kept well within any legislated requirements and small compared to that received from the natural environment There have been instances during the development of the industry when inadequate procedures and precautions were used which subsequently resulted in releases of radioactivity, but their environmental impact has been very small. New technology will be required for some wastes in the future.

Storage of high activity liquid wastes in tanks of modern design is safe and satisfactory in the short term until facilities for solidifying waste and engineered storage are constructed in the 1980s. The required technology is already available. This interim solution will provide up to 100 years for extensive assessment and evaluation of the wide range of permanent solutions which have been proposed in order to determine the most acceptable method for ultimate disposal. Until then, the nuclear industry has a responsibility to maintain strict surveillance of high activity wastes but this need is not unique; for example, every water storage dam above an inhabited valley must be maintained and monitored by each generation. Based on present technology, the best method for ultimate disposal appears to be placing solid waste in a geological formation on land. Disposal in salt or hard rock presents no major engineering problem but requires confirmation that wastes will remain permanently out of man's environment.

11. FURTHER READING

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TABLE 1

RADIOACTIVE WASTES AND MANAGEMENT PRACTICES IN THE NUCLEAR INDUSTRY

Radioactive Waste Stream	Contaminants	Typical Waste Management Practice
Uranium Mining and Milling		
Air from mines	Radon	Diluted and discharged to atmosphere
Process/ventilation air from mills	Radon, ore dust	Filtered/scrubbed, discharged to atmosphere
Mine and runoff waters	Radium, uranium,heavy metals	Used in mill, excess diluted and discharged
Process waste solutions	Radium, uranium, acid, inorganic salts, heavy metals, sulphate etc.	Neutralised with lime; precipitated solids stored in tailings retention system, clear liquor recycled to plant
Solid waste tailings	Radium, uranium	Neutralised with lime; stored permanently in tailings retention system, eventually vegetated and stabilised.
Uranium Hexafluoride Production		
Process gases/ventilation air	Uranium, fluorides, nitrogen oxides	Filtered/scrubbed, discharged to atmosphere
Process waste solutions	Uranium,acid, inorganic salts, fluorides, nitrates etc.	Neutralised with lime; precipitated solids retained in dams or buried, clear liquor held in dams or discharged and diluted
Low level solid waste		Packaged for ground burial
Isotope Enrichment		
Process gases/ventilation air	Uranium, fluorides	Discharged to atmosphere
Low level liquid effluents	Traces of uranium, fluorides, nitrates etc.	Neutralised with lime; precipitated solids retained in dams or buried, clear liquor held in dams or discharged and diluted
Low level solid waste		Ground burial
Fuel Fabrication		
Process gases/ventilation air	Uranium, fluorides	Filtered/scrubbed, discharged to atmosphere
Low level liquid effluents	Uranium, fluorides, nitrates, ammonia	Neutralised with lime ;precipitated solids retained in dams or buried, clear liquor held in dams or discharged and diluted
Low level solid waste		Ground burial

TABLE 1 (Continued)

RADIOACTIVE WASTES AND MANAGEMENT PRACTICES IN THE NUCLEAR INDUSTRY

Radioactive Waste Stream	Contaminants	Typical Waste Management Practices
Reactor Operation		
Offgases	Fission product noble gases(e.g. krypton, xenon), iodine isotopes, activated nitrogen etc.	Filtered (absolute), adsorbed on charcoal beds, diluted and discharged to atmosphere
Blowdown water, coolant leakage	Fission products, corrosion and activation products, tritium	Filtered, purified by ion exchange, recycled/diluted and discharged
General chemical liquid waste	Fission products, activation products, inorganic salts	Evaporated, treated by flocculation-precipitation or ion exchange
Medium level solid waste	Spent ion exchange resins, sludges from waste treatment	Incorporated in bitumen/cement prior to storage/ground burial
Low level solid waste		Ground burial
Reprocessing of Irradiated Fuel		
Offgases	Fission product noble gases(e.g. krypton, xenon) isotopes, tritium	Treated to remove iodine isotopes, filtered (absolute), diluted and discharged
High level liquid waste	Fission products, actinides, acid	Evaporated, stored in tanks on interim basis, solidified
Medium level liquid waste	Fission products, actinides, fission products, acid	Evaporated, concentrate to high level liquid waste treatment, condensate to low level liquid waste treatment
Low level liquid waste	Fission products, acid, inorganic salts	Treated by ion exchange or flocculation-precipitation; sludges resins etc to solid waste treatment, purified water recycled/ discharged
High level solid waste (e.g solidified high level liquid waste, chopped fuel cladding)	Fission products, actinides, activated zirconium	Interim storage in engineered facilities, ultimate storage/ disposal to be determined
Medium level solid waste		Incorporated in cement/bitumen for ground burial
Low level solid waste		Ground burial

TABLE 2

RADIOACTIVITY OF IMPORTANT LONG-LIVED FISSION PRODUCTS IN HIGH ACTIVITY LIQUID WASTE

(Basis: One year of operation of a typical 1000 megawatt (electrical) light water reactor)

Isotope	Half-life	After 1 year (curies)	After 10 years (curies)	After 100 years (curies)	After 1000 years (curies)
Strontium-90	29 years	2010 000	1610 000	174 000	†
Yttrium-90*	2.6 days	2010 000	1610 000	174 000	
Zirconium-93	950 000 years	50	50	50	50
Niobium-93m	12 years	6	23	50	50
Technetium-99	213 000 years	380	380	380	380
Ruthenium-106	369 days	7250 000	14 600		
Rhodium-106*	2.2 hours	7250 000	14 600		
Caesium-134	2 years	4680 000	223 000		
Caesium-137	30 years	2790 000	2270 000	281 000	
Barium-137m*	2.6 minutes	2620 000	2130 000	263 000	
Cerium-144	284 days	12 100 000	4 000		
Praseodymium-144*	17 minutes	12 100 000	4 000		
Samarium-151	93 years	32 900	30 800	15 000	12

* *Indicates short-lived 'daughter' of the isotope directly above it in the table.*

† *Blanks indicate that radioactivity has decayed to less than one thousandth of a curie.*

TABLE 3

RADIOACTIVITY OF TRANSURANIUM ELEMENTS IN HIGH ACTIVITY LIQUID WASTE

(Basis: one year of operation of a typical 1000 megawatt (electrical) light water reactor)

Isotope	Half-life	After 10 years (curies)	After 100 years (curies)	After 1000 years (curies)	After 10 000 years (curies)	After 1 million years (curies)
Neptunium-237	2140 000 years	9.1	9.2	9.8	10	7.3
Neptunium-239	2.35 days	480	480	440	200	
Plutonium-238	87.8 years	2500	1300	5.9		
Plutonium-239	24 390 years	43	44	55	110	
Plutonium-240	6540 years	120	230	210	84	
Plutonium-241	15 years	8500	130	8.4	3.9	
Plutonium-242	387 000 years	0.2	0.2	0.2	0.2	0.03
Americium-241	433 years	4300	4000	950	3.9	
Americium-242m	152 years	230	150	2.6		
Americium-243	7370 years	480	480	440	195	
Curium-242	163 days	190	130	2.1		
Curium-243	28 years	80	11			
Curium-244	17.9 years	44 000	1400			
Curium-245	8500 years	9.1	9.0	8.4	3.9	
Curium-246	4760 years	1.8	1.8	1.6	0.4	

This table was calculated on the assumption that, because of incomplete recovery, 0.5 per cent of plutonium in the spent fuel enters the high activity wastes. Blanks indicate that radioactivity has decayed to less than one thousandth of a curie.

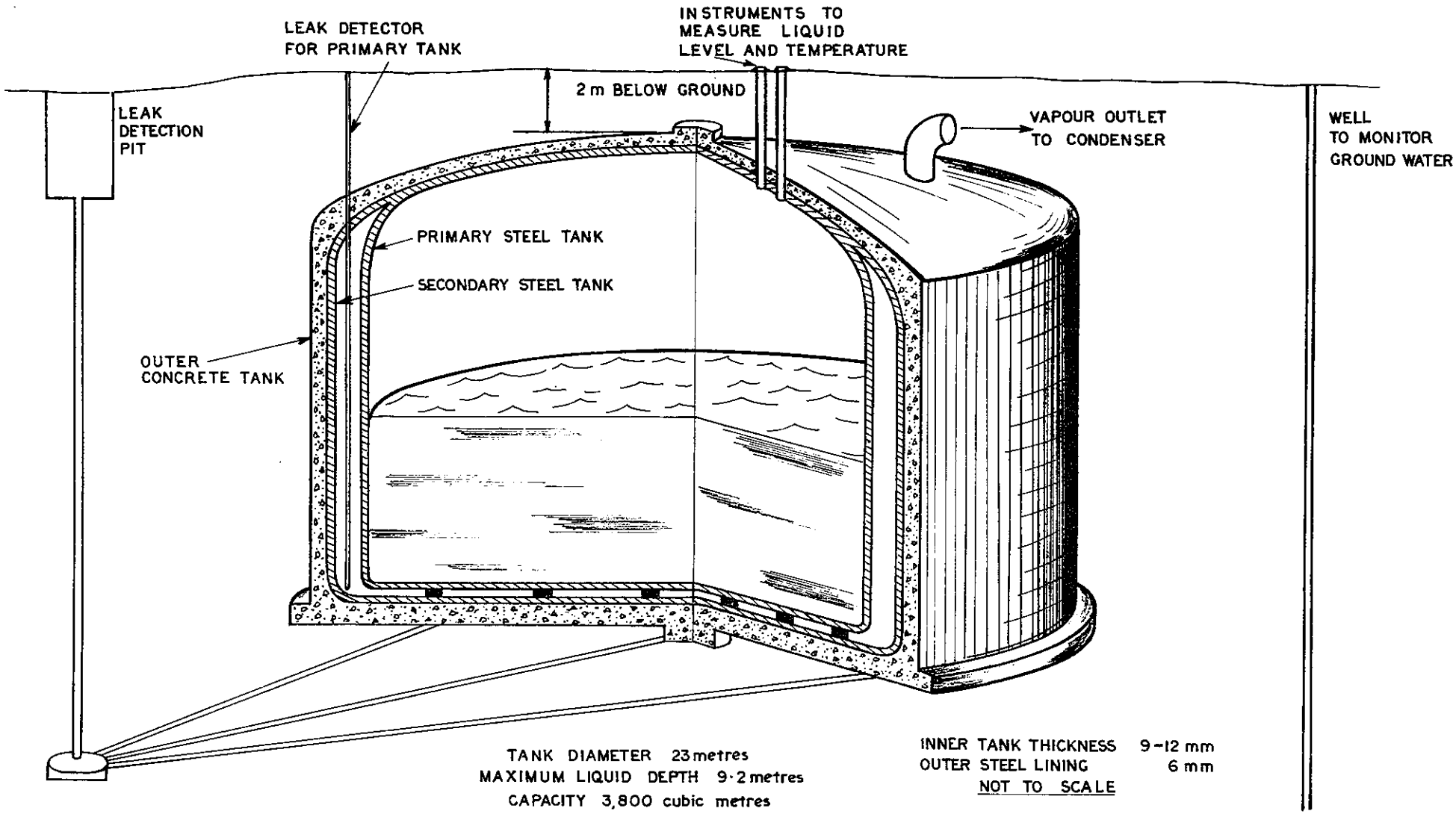

FIGURE 1. MODERN MILD STEEL TANK FOR STORAGE OF ALKALINE, HIGH ACTIVITY, LIQUID WASTE (Hanford, USA)

APPENDIX

HIGH ACTIVITY WASTE MANAGEMENT AROUND THE WORLD

The following Table summarises current practice and future plans for high activity waste management in selected countries with a significant commitment to nuclear power. In most countries, only small quantities of high activity wastes have been generated to date and these are generally stored as liquids in tanks. There is widespread recognition of the need to solidify liquid wastes in the future and many countries have pilot plants where specific solidification processes are being developed. The general consensus favours conversion to a high melting point, glassy solid which is considered the safest form for interim storage or disposal. The selection of a method for ultimate disposal is regarded as a long term rather than immediate goal.

CURRENT PRACTICES AND FUTURE PLANS FOR HIGH ACTIVITY WASTE

Country	Current practice	Future plans
USA	**Wastes from Government Operations**	
	Hanford, Washington - Liquid wastes are made alkaline and stored in mild steel tanks. Caesium-137 and strontium-90 are chemically separated from high heat wastes, encapsulated and stored in water-cooled basins. Liquid wastes are gradually being solidified by evaporation to a salt cake that is stored in existing tanks.	All high activity wastes are to be solidified as soon as practicable. Long-term options being evaluated include storage in existing tanks or vaults, storage on-site in underground caverns, or shipment to off-site federal repository.
	Savannah River, South Carolina - Liquid wastes are made alkaline and stored in mild steel tanks. Program under way to evaporate and cool liquid wastes to form a salt cake. Saturated salt solutions are stored in existing tanks.	
	National Reactor Testing Station, Idaho - Acidic waste solutions stored in stainless steel tanks prior to calcination in Waste Calcining Facility and interim storage in stainless steel bins.	
	Wastes from Commercial Reprocessing	
	No commercial plants are currently operational. The Nuclear Fuel Services Plant in New York State commenced operation in 1966 but is now shut down while the plant capacity is being expanded. Most high activity wastes from this plant were made alkaline and are stored in a mild steel tank but small quantities of special wastes are stored in a stainless steel tank.	The Barnwell Nuclear Plant in South Carolina is expected to commence operation in 1977. After reprocessing, all high activity liquid waste is to be converted into an immobile form within 5 years and must be transferred to a national repository within 10 years. Pilot plant demonstration of waste solidification processes from 1966 - 1972 at Hanford established the necessary technology. Currently, assessments of alternatives for both interim and ultimate storage are in progress.
UK	Liquid wastes are stored as acidic solutions at Windscale and Dounreay reprocessing plants in stainless steel tanks.	Storage of wastes as liquids is considered safe in the near term. The FINGAL process to solidify wastes into borosilicate glass was investigated from 1958 to 1968. An improved glass making process (HARVEST) is being developed and there are plans to begin solidifying wastes in the mid 1980s. Storage methods that allow solidified wastes to be retrieved are favoured.

APPENDIX (Continued)

Country	Current practice	Future plans
France	Liquid wastes are stored as acidic solutions at the Marcoule and La Hague reprocessing plants in stainless steel tanks. The PIVER pilot plant to solidify wastes into borosilicate glass has been operating since 1969.	Interim storage of solid waste canisters under water is proposed with subsequent transfer to an air-cooled facility.
West Germany	Liquid wastes from WAK reprocessing pilot plant are stored in stainless steel tanks. Studies of solidifying wastes into borosilicate and phosphate glass are in progress.	First radioactive glasses will be produced in the VERA pilot plant in 1976/77. High-level liquid wastes will be converted into glasses after a 3 to 5 year cooling period. Salt formation at Asse is being studied for ultimate disposal.
USSR	Liquid wastes stored in stainless steel tanks. Solidification processes to produce phosphate glasses have been investigated on a laboratory scale with radioactive wastes and on a pilot plant scale with inactive simulated wastes.	Industrial scale plant to glassify wastes is expected to begin operation about 1980. Liquid injection into deep geological formations is also being considered.
Canada	Engineered storage of small numbers of irradiated fuel assemblies.	Storage of fuel without reprocessing in water or air-cooled vaults is considered satisfactory for at least 75 years. If economically attractive, fuel will be reprocessed at a later date.
India	Liquid wastes stored as acidic solutions in stainless steel tanks.	Two waste immobilisation plants using a batch glass-making process are expected to be operating by about 1977. Solidified wastes will be stored in water-cooled ponds.
Belgium	Liquid wastes from Eurochemic reprocessing plant are stored in stainless steel tanks.	Calcination and glassification processes are being considered for waste solidification.
Japan	No significant quantities of high level wastes have been produced.	A reprocessing plant is presently under construction. Acidic wastes will be stored in stainless steel tanks for periods of up to five years. It is proposed to construct a pilot solidification plant by 1979.
Italy	EUREX pilot reprocessing plant began operation in 1970. Small quantities	Batch solidification to form borosilicate or phosphate glasses

GLOSSARY

The following definitions are provided for the reader not familiar with some nuclear and other terms used in this paper. The explanations are drawn from standard glossaries. *

activation	The process of inducing radioactivity
alpha-particle	A helium 4 nucleus emitted during a nuclear transformation. *Alpha-decay* is radioactive decay in which an alpha particle is emitted; whence *alpha-radioactivity, alpha-activity, alpha-emitter.*
biosphere	That part of the Earth and the atmosphere surrounding it which is able to support life.
containment	The prevention of release, even under the conditions of a reactor accident, of unacceptable quantities of radioactive material beyond a controlled zone; also the containing system itself.
coolant	A substance used to remove heat from a primary source such as a reactor core.
curie(s)	A unit of activity defining the number of spontaneous nuclear disintegrations occurring per unit time; 1 curie = 3.7×10^{10} disintegrations per second; whence picocurie, microcurie and similar sub-multiples.
enrich	To increase the abundance of a particular *isotope* in a mixture of the *isotopes* of an element; whence *enrichment, isotope enrichment.*
fast reactor	A reactor in which *fission* is induced predominantly by *fast neutrons*, that is, neutrons moving at high speeds; whence *fast breeder* reactor.
fission	The splitting of a heavy nucleus into two approximately equal fragments. This is accompanied by the emission of neutrons and release of energy; whence *fission products*, the atoms formed in the fission process.
fissionable	Capable of undergoing fission by any process. In British usage it is equivalent to *fissile* but in US usage, *fissile* is restricted to interaction with slow neutrons.
fluidised bed	A bed of finely divided solids which is caused to behave like a fluid by suspending it in a moving gas or liquid.

ground-water	Water naturally contained in the subsoil.
half-life	The time taken for the activity of a radioactive substance to decay to half its original value. The term is often extended to other processes.
hexafluoride	The gaseous compound uranium hexafluoride (UF_6), used in diffusion and centrifugal uranium enrichment plants. (Abbreviated 'hex'.)
isotopes	Varieties of the same element having different masses; whence *isotopic*.
megawatt	The normal practical unit of power station capacity (one million watts). Sometimes megawatts (electrical) and megawatts (thermal) outputs are signified.
monitor	A device used to measure the level of *ionising radiation* or quantity of radioactive material and possibly to give warning of departure from prescribed limits. Also a person who uses a *monitor*.
neutron	A nuclear particle having no electric charges and the approximate mass of a hydrogen nucleus; whence *neutron absorption, neutron activation, neutron capture*.
noble gases	The gases helium, neon, argon, krypton, xenon and radon-222 which are inert to all the usual chemical reactions.
nuclide	A species of atom characterised by its mass number, atomic number and nuclear energy state. See *radionuclide*.
particulate	Having particle form. Can be used to describe matter (in powder form) or radioactive particles.
radiotoxicity	Toxicity due to radioactivity.
radon	A gaseous product of the disintegration of radium.
tailings (tails)	The rejected portion of an ore in mineral processing; waste.
transmutation	Change of atomic number of an atom due to bombardment by high energy particles.
transuranium elements	The artificially produced elements of atomic number 93 and higher which have heavier and more complex nuclei than uranium.
tritium	A (heavy) *isotope* of hydrogen (mass number 3).

yellowcake — The uranium oxide concentrate produced by a uranium treatment plant.

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